Bio-Optical And Nutrient Responses To Physical Forcing Processes During Monsoons In The Northwest Indian Ocean

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LONG TERM GOALS

The overall goal of this research program is to understand the interaction between physical processes, nutrient fluxes, and biological and optical responses within the upper ocean layers of both coastal and open ocean regions.

OBJECTIVES

The objectives of this research are to characterize the distributions of physical, biological and optical variability within the Arabian Sea as a function of the annual monsoon cycle. In particular, we are examining the processes contributing to nutrient fluxes into the upper layer, the interaction of the euphotic zone and surface mixed layers, the spatial scales of variability within the upper layer, and the bio-optical responses to these processes.

APPROACH

Spatial variability of physical, bio-optical and bio-acoustic variables were sampled with a SeaSoar (Brink [WHOI] and Lee [UW-APL]) carrying sensors for temperature, conductivity, chlorophyll fluorescence, photosynthetically available radiation (PAR), beam transmission (C_{660}), DOM fluorescence (P. Coble, USF), dissolved oxygen (C. Langdon, LDEO), and acoustic back-scatter (Holliday, Tracor). The SeaSoar was used to map 2-D and 3-D distributions of these variables using long transects and radiator patterns, respectively. During SeaSoar mapping nutrients were measured continuously from the ship's underway seawater system. Hydrographic sections were obtained along the southern JGOFS line, on a cross-shelf transect at about 19° 20'N, just north of Ras al Madraka, and a high resolution transect associated with a SeaSoar radiator pattern. Other sections were added opportunistically. Hydrographic variables included T, S, dissolved oxygen, nutrients, extracted chlorophyll (Yentsch and Phinney) and chlorophyll fluorescence, C_{660}, and PAR.

Analysis of the data set includes three major components. The first component is to examine the processes and scales of variability that are apparent in the Seasoar and underway data sets. The second component is to examine the bio-optical variability within the SeaSoar data set, including the examination of basic relationships between beam attenuation, chlorophyll fluorescence, and the attenuation of PAR, the spatial interaction of the euphotic zone depth and mixed layer depth, and modeling of the spatial distribution of primary productivity based on beam attenuation, chlorophyll fluorescence, and PAR. The third component of analysis is to examine the relationships between water

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mass and nutrient variability, the implications of this variability to vertical nutrient fluxes, and the impact of the suboxic layer and denitrification on upper ocean processes.

WORK COMPLETED

During the past year, we have continued work on the small scale hydrographic variability and the processes and scales of variability of optical characteristics of chlorophyll fluorescence and beam transmission which reflect phytoplankton biomass. Analysis of the scales and overall structure are described in the paper by Lee, Jones and Brink (1999). We have continued work on the interaction between euphotic zone and mixed layer depths in various regions of the NW Arabian Sea. With Seasoar detailed maps of this variability can be constructed which show this variability in complex regions such as an upwelling filament (Figure 1). In addition, we have applied photosynthesis/light curves to the data sets to estimate the three-dimensional distributions of primary productivity that results during each of the four cruises. The work on primary productivity has been performed in association with R. Toon and S. Lohrenz (Toon, et al., 1999).

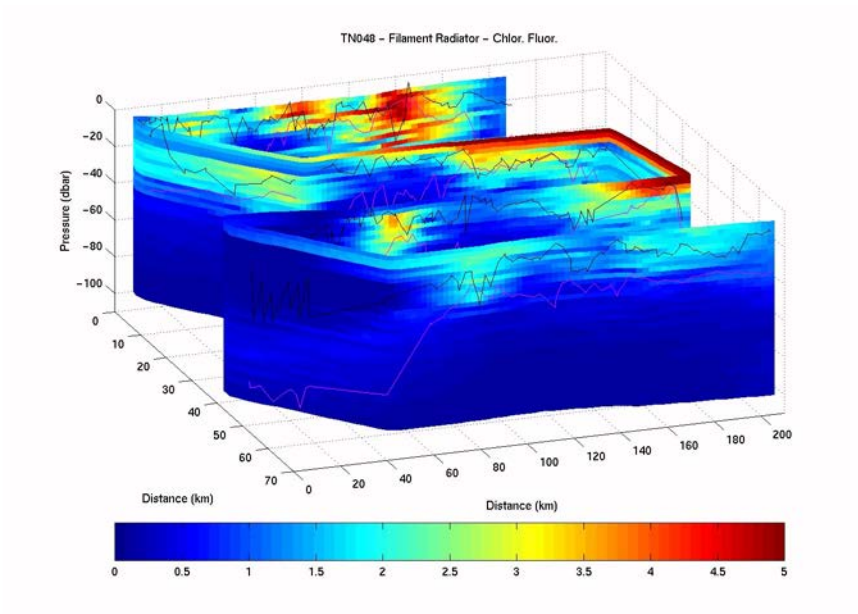

Figure 1. Chlorophyll fluorescence from the Seasoar section through the upwelling filament extending off the coast of Oman during the SW Monsoon in early July 1995. The filament can be seen in the chlorophyll fluorescence with its two branches that are near to each other in the leg at the back of the figure and spread farther apart farther offshore, toward the front of the figure. Throughout most of this radiator the euphotic zone depth (magenta line) is significantly deeper than the mixed layer depth (black line), except in the core of the filament where the euphotic zone may be shallower than the mixed layer depth.

RESULTS

During the SW monsoon upwelling filaments contributed to seaward fluxes of nutrients and phytoplankton biomass. The filaments were observed near the mooring (~550 km offshore). High ammonium concentrations in the filament indicated significant nutrient regeneration activity and suggest grazing activity. Subduction was evident as the filament advected offshore. Physical analysis of

the Seasoar data set by Lee and Brink (WHOI) suggests little evidence for wind stress curl driven upwelling during either July or September-October 1995 (Lee et al., 1999). Distributions of water masses and nutrients support this conclusion (Brink et al., 1998). This indicates that the broad scale productivity occurring at the end of the SW monsoon season is the result of horizontal advection from the coast, as suggested by Young and Kindle (1994).

Multivariate analysis has been used on the hydrographic data set to further understand the annual variability along the southern JGOFS line in the Arabian Sea. Using data from 10 cruises (our four Seasoar cruises and six JGOFS cruises [data provided by Codispoti and Morrison]) and from the upper 500 m, we were able to evaluate the major regions of variability associated with the nutrient variables (Zheng et al., in prep.). Ammonium variability indicative of nutrient regeneration over the 10 cruise series had its dominant variability within the upper 100m along the JGOFS line. This component was highest during both the NE and SW monsoons apparently coupled with primary productivity and grazing in the upper layer. Nitrite, in contrast, was most dominant between 125 and 325 m, but with and offshore spatial maximum in variability beyond 800 km from the coast in the depth range of 125-225 m, perhaps indicating the influence of the well documented denitrifying region in the eastern half of the Arabian Sea (e.g. Naqvi, 1991).

During the SW monsoon there were distinct populations that were apparent in the bio-optical relationships between beam attenuation at 660 nm (C_{660}), chlorophyll fluorescence and the apparent optical property, K_{par}. In the upwelling filament that extended seaward from the coast the slope of the K_{par} / C_{660} was low compared with the slopes further offshore where mixing was deeper, indicative of both photoadaptation and perhaps species changes. In the filament nearshore the mixed layer depth was shallower than the euphotic zone depth and therefore the water column was conducive to high productivity resulting from the upwelled nutrients (Figure 1). Farther offshore, high wind stress caused deep mixing of up to 65m but the mixing did not penetrate the pycnocline. The mixed layer was generally shallower than the euphotic zone depth due to very little phytoplankton biomass in the mixed layer due to the lack of nutrient availability. During the late NE monsoon in February, mixed layer depths were often deeper than the euphotic zone depth and deeper than during the SW monsoon, contributing to the vertical nutrient supply, and the inability of the phytoplankton to utilize all of the available nutrients.

Spatial scales of chlorophyll fluorescence, density and salinity from the mixed layer and pycnocline have been calculated by Craig Lee (Lee et al., 1999). Under most conditions the e-folding scales for phytoplankton are 10-20 km and significantly less than the scales for physical variables. This indicates that there are either biological processes or unresolved physical processes that control the spatial scales of the phytoplankton.

IMPACT/APPLICATIONS

The results from the Arabian Sea indicate that while the responses to the NE and SW monsoons are predictable at a gross level, the region is highly complex as evidenced by water mass variability, small spatial scales, and spatial an temporal variability of the forcing processes. Traditional shipboard hydrography will under sample the variability because of the very short spatial scales. SeaSoar mapping enables us to resolve much of the smaller scale variability of both physical and biological variables and to evaluate mesoscale patterns and processes.

TRANSITIONS

The SeaSoar technology has being implemented with additional bio-optical sensors for use in the ONR-funded Japan/East Sea study currently in progress. During this study we are examining the physical and bio-optical dynamics associated with the subpolar front as well as the interaction between the continental shelf and the open sea off of South Korea.

RELATED PROJECTS

This research effort is highly collaborative with investigators in both the ONR-funded Forced Upper Ocean Dynamics Program (FUOD) and NSF-funded JGOFS Program. Our major collaboration has been with Dr. Ken Brink (WHOI) and Dr. Craig Lee (U. Washington). We have complemented their analysis of the physical data set from the Seasoar with analysis of the bio-optical data set. We collaborated with the JGOFS hydrographic team (L. Codispoti and J. Morrison) to integrate the hydrographic observations from the entire Arabian Sea data set. This interaction resulted in one major overview paper (Morrison, et al., 1998).

In addition, we have collaborated with Drs. Dickey (UCSB) and Marra (LDEO) to compare Seasoar bio-optics with moored bio-optical observations from the central mooring and to investigate the role of convective mixing and stratification processes in driving the high productivity during the NE Monsoon (Wiggert et al., 1999).

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